EXPLOSIVE VENTING ON EUROPA? A PRELIMINARY ASSESSMENT. S. A. Fagents[1], R. Greeley[1], and the Galileo SSI Team, [1]Department of Geology, Box 871404, Arizona State University, Tempe, AZ 85287-1404; e-mail fagents@atlas.la.asu.edu.

Galileo images of the surface of Europa reveal that many dark lineaments and elliptical patches have diffuse outer margins [1]. Explosive venting of cryovolcanic mixtures of water, ice and silicate components is one possible origin for these features. Volatiles such as CO or CO_2 dissolved in water/ice at depth could drive an eruption in a manner analogous to the way in which H_2O and CO_2 drive eruptions of silicate magmas on the terrestrial planets. Rhadamanthys Linea is a ~2000 km long lineament trending WNW-ESE in the northern hemisphere of Europa, and has dozens of dark elliptical patches superposed along its length. This relationship is reminiscent of halos of scoria along terrestrial volcanic fissure zones. Assuming a cryovolcanic origin, measurements of diameters of 70 such patches allow us to make inferences about the dimensions and dynamics of the eruptive plumes required to produce such deposits. Assuming the eruptions constitute gas-rich ejections of sub-mm water/ice particles (± silicates), a simple model of ballistic emplacement in the low-gravity and low-pressure Europan environment suggests that the Rhadamanthys dark deposits could be produced by plumes ranging up to 27 km in height, implying eruption velocities in the range 40 to 265 m s^{-1}. By relating these eruption velocities to the amount of volatiles required to drive eruptions of these magnitudes, we are able to speculate on the conditions in the cryomagma source region.

Eruptive Models

Analysis of Voyager data of Io's eruptive plumes suggested that two end member scenarios exist for explosive venting into low atmospheric pressure environments [2-4]. If the erupting mixture expands to ambient pressure through a flaring conduit, a "balanced plume" will exist and the eruptive products will follow ballistic trajectories above the surface, forming a symmetrical, umbrella-shaped plume [4]. If the emerging mixture is overpressured, shock phenomena will interact with the erupting material to produce complex plume structures [4].

The eruption of pure water from depth onto the icy Europan surface is problematic because of the negative buoyancy of water with respect to ice. The presence of dissolved volatile species is crucial to the ascent of cryomagmas on icy satellites [5]: the alleviation of confining pressure during ascent enables volatile exsolution and thus creates a positive driving force. Consideration of the propagation of water-filled cracks from the base of a thin ice crust on Europa indicates that exsolution of plausible volatile species (CO_2, CO, CH_4, SO_2) would take place at the dike tip [6]. Linear fracture mechanics suggests the gas-filled crack tip would pinch off and rise rapidly, entraining some amount of water. Eruptions at the surface may initially comprise predominantly of gas, and then be followed by a water spray or foam.

Analogy with Io's Volcanism

Although the nature of volcanic products on Io and Europa undoubtedly differ, the manifestation of eruptive activity may be similar in such low-pressure environments. It has been proposed that Ionian plumes are very gas-rich [7], such that the particulate material consists of sulfur droplets and condensing SO_2 [2,4]. Gas-rich plumes would also result from the above described model of Europan volcanism [6]. Although the details of magma disruption processes are poorly understood, the low ambient pressure (~10^{-7} Pa [8]) implies that thorough disruption of magmatic liquid would occur, perhaps producing similar particle/droplet size distributions for both Ionian and Europan volcanism, despite magma compositional differences.

Dimensions of Io's eruptive plumes were obtained from Voyager image data [3], which indicate that plume height:width ratios lie between 0.2 and 0.9, with most falling in the range 0.2 to 0.4. Provided the vent geometries and plume particle size distributions are similar, ballistic plume structures should be essentially independent of magma composition and planetary gravity. Thus, the range of plume height:width ratios should be similar on Io and Europa.

Rhadamanthys Linea

The association of dark patches with Rhadamanthys Linea is suggestive of terrestrial scoria deposits along eruptive fissures, which indicates a possible volcanic origin for these features. The patches could be the result of localized explosive venting of cryomagma (± silicate particles). The dark color of the spots could be the result of a few percent of silicate material being entrained in the eruptive plume and deposited near to the vent, or be the result of the varying photometric properties of ice of differing grainsizes. Diameters (measured perpendicular to the trend of the linea) of 70 dark patches lie in the range 3 to 30 km, with a mode near 12 km.

Assessment of Eruption Conditions

If it is assumed that deposit diameter is equivalent to plume width, and it is further assumed that Europan plume height:width ratios would be similar to those on Io (the ranges of particle size distributions and eruption velocities are likely to be similar in near-vacuum environments), the plume height:width ratios for Io can be used to obtain the likely range of plume heights on Europa. Using the simplest eruption model (that of a ballistic "balanced" plume [2-4]) the range of eruption velocities required to produce plumes in this height range can be found. Table 1 shows that for deposit widths in the range 3 to 30 km, plume heights of 0.6 (h/w=0.2) to 27 km (h/w=0.9) are indicated.

Table 1. Plume heights required to produce minimum, modal and maximum deposits measured, as a function of h/w.

Spot diameter w **(km)**	**Plume height** h **(km)** h/w=0.2	h/w=0.9
3	0.6	2.7
12	2.4	10.8
30	6.0	27

Employing the classical ballistics equation, $h=u_0^2/2g$, the eruption velocity, u_0, can readily be obtained from the plume height. This can be equated with reasonable accuracy for a balanced plume to the asymptotic velocity, u_m, attained by erupting gas-particulate material in low-pressure environments [5]:

$$u_m = \sqrt{\frac{2\gamma R T_i n}{m(\gamma - 1)}} \qquad (1),$$

in which R is the gas constant, g and m are respectively the ratio of specific heats and the molecular weight of the volcanic gas, n is the mass fraction of gas in the ejected material, and T_i is the temperature from which the gas expansion begins. This expression can be used to place constraints on the mass ratio of gas to particulate material in the erupting mixture. Table 2 shows the gas mass fractions of plausible volatile species that are required to attain different eruption velocities using T_i=273 K, γ=1.3, and R=8314 $m^2\ s^{-2}\ K^{-1}$.

Consideration of CO_2 equilibrium suggests 0.003 to 0.21 mole fraction may be incorporated in liquid water and ice (as clathrates) [6] at the base of a 10 to 100 km brittle icy crust. The values in Table 2 indicate that a significant concentration in excess of solubilities in potential cryomagma is required to produce most of the predicted eruption velocities and plume heights for the Rhadamanthys deposits.

Table 2. Weight percent of different volatiles required to achieve various predicted gas velocities.

Velocity* **(m s^{-1})**	**CO_2** m**=44**	**CO** m**=28**	**SO_2** m**=64**	**CH_4** m**=18**
40[a]	0.36	0.23	0.51	0.15
102[b]	2.3	1.5	3.3	0.95
265[c]	15.7	10	22.3	6.4

*Velocities predicted to produce [a]minimum plume h/w and deposit diameter (0.2 and 3 km, respectively); [b]modal plume h/w and deposit diameter (0.3 and 12 km); [c]maximum plume h/w and deposit diameter (0.9 and 30 km).

Summary

Using simple models, this preliminary study suggests that the gas mass percentages required to achieve the eruption velocities (40 to 265 m s^{-1}), plume heights (0.6 to 27 km) and deposit widths (3 to 30 km) for the Rhadamanthys Linea spots typically exceed the maximum cryomagma gas mass fraction indicated by solubility relationships (at least for CO_2). If larger dark patches on the Europan surface (e.g., "freckles") are the result of explosive cryovolcanic processes, still greater gas concentrations are required. It is therefore likely that explosive venting on Europa does not typically involve ascent and fragmentation of homogeneous bubble-water mixtures (as is more typical for basaltic lava fountains). Thus some mechanism for gas segregation is required to initiate explosive eruption of the cryovolcanic mixture. These findings lend support for the eruption model of Crawford and Stevenson [6], in which explosive venting is the result of propagation of dikes containing large proportions of gas separated from the cryomagma.

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